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Collisionless Shocks Experiments Using NIF

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Final Report for NIF Concept Development Grant
"Collisionless Shocks Experiments Using NIF"

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Executive Summary

The goal of this project is to explore the feasibility of using NIF to create laboratory platforms to study relativistic and non-relativistic collisionless shocks in the laboratory, and to study the scalability and relevance of such laboratory experiments to astrophysical shocks. This is a very broad topic. During the past 12 months, we made major advances in at least one area: development of a capable, flexible, robust platform for the study of nonrelativistic collisionless shocks using NIF. Hence this report will focus on these results. Study of viable platforms for relativistic collisionless shocks is ongoing. Some preliminary concepts will be discussed here in this Report.

1. New Platform for Non-relativistic Collisionless Shocks

The main challenge of creating collisionless shocks using lasers, and studying their structure and evolution, is the small spatial scale and short duration of laser-created plasmas. To be collisionless, the plasma must have long coulomb mean-free-paths compared to the plasma scale height, requiring low density and high temperature. Yet it must also have collisionless mean-free-paths (related to the plasma skin depth and gyroradii) short compared to the plasma size in order to form a shock, requiring high density and strong magnetic fields. These two requirements are often in conflict. Even when they are not, the small space and time domain of laser-created plasmas means that the collisionless shock can only exist for a brief time and propagate a short distance before these conditions are violated, making the detection and diagnostic of the shock extremely difficult and challenging.

The current approach to creating nonrelativistic collisionless shocks using lasers, as adopted by the ACSEL consortium led by Drs. H.S. Park (LLNL) and A. Spitkovsky (Princeton), is to use supersonic colliding plasma jets. Two opposing supersonic jets are created by irradiating two low-Z (e.g. plastic) flat targets facing each other. For a given laser intensity (e.g. 10 coincident Omega beams for each target), if the collision occurs at an optimal distance from each target (e.g. 4 mm), then numerical simulations suggest that a collisionless shock may be formed at the stagnation point. So far results from the Omega experiments have been inconclusive. The main difficulty is the *small dynamic range* of the colliding plasma jet parameters.

Over the past six months, using computer simulations with the newly upgraded FLASH code, our team at Rice has identified a *new experimental platform* for laboratory astrophysics involving multi-beam high energy lasers. It is based on the *hollow ring laser* configuration: instead of focusing all laser beams onto a single spot, the same lasers are focused to form a circular hollow ring pattern. Preliminary FLASH results show that, because of the rocket nozzle effect, the hollow ring configuration produces a much more highly collimated supersonic outflow, with *axial density, temperature and flow velocity much higher* than those achievable by focusing all beams onto a single target spot. By varying the radius of the hollow ring, we find that a much larger dynamic range of jet parameters (density, temperature, velocity, Mach number, opening angle, collisionality etc) can be achieved, providing a much more capable, flexible and robust platform for laboratory astrophysics experiments utilizing supersonic outflows. This new platform has specific and important applications to the study of collisional and collisionless shocks, plus many other laboratory astrophysics topics, such as shear flows, jet propagation and stability, magnetic field generation, to name a few.

Figure 1 shows a 2-D FLASH output of a supersonic jet launched by a ring laser with the equivalent energy of 10 Omega beams, compared to a jet launched by all 10 beams hitting the same spot. The jet launched by the ring laser is much more collimated. Figure 2 compares the electron density profile time history for the two cases. Figure 3 compares the electron and ion on-axis density, temperature, velocity and Mach number at 4 mm from target as functions of time for different ring laser radii. We see that the density, temperature and axial velocity are much higher as the ring laser radius increases from zero to 800 microns, which appears to be the optimal radius for the Omega laser intensity and duration.

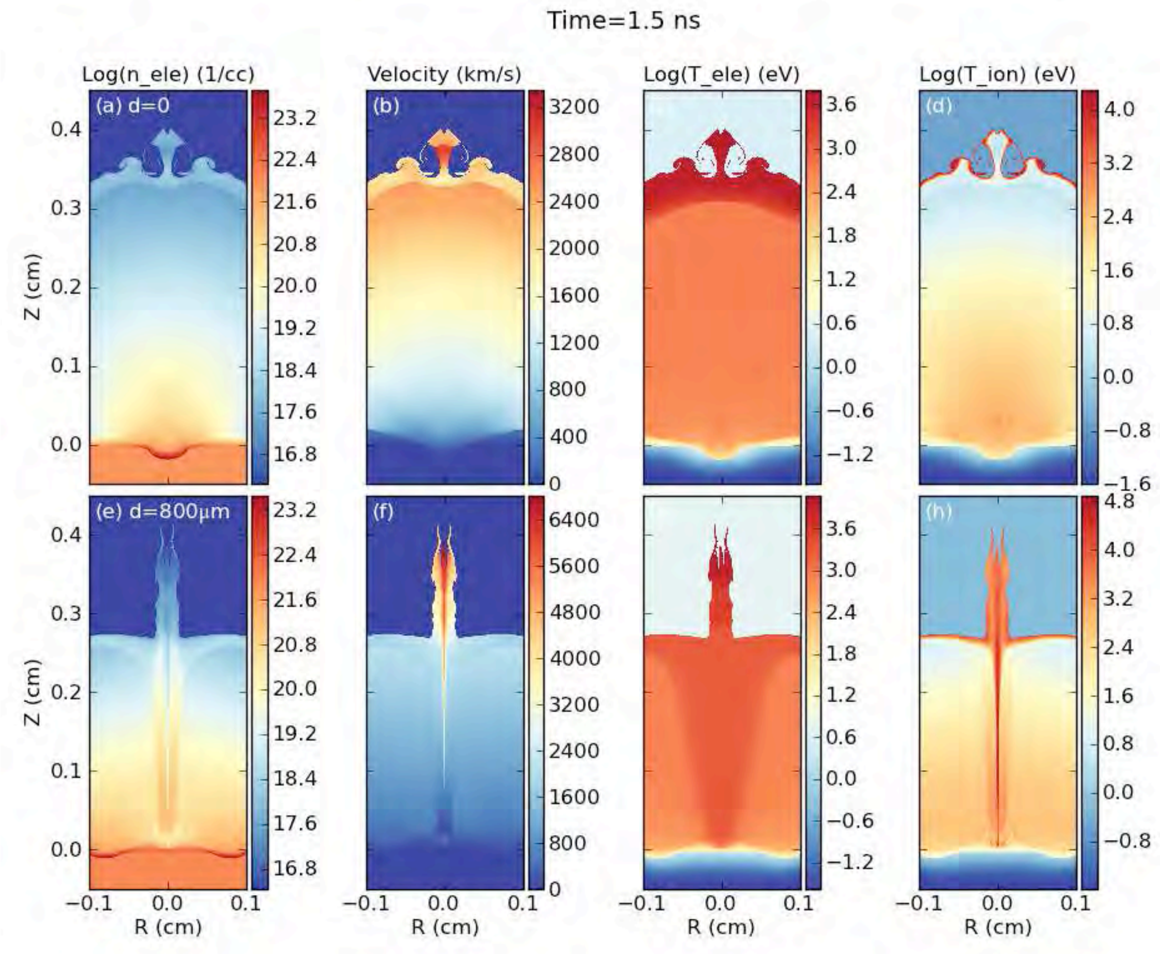


Fig.1. Comparison of 2D-FLASH code outputs for a CH target irradiated by a solid (d=0) laser beam (a,b,c,d), with that irradiated by a hollow ring beam with d = 800 microns (e,f,g,h). d is the distance from the ring center to the half-width of the ring, which itself has full width = 250 microns. The laser parameters are equivalent to 10 Omega beams (from Fu et al PRL submitted 2012).

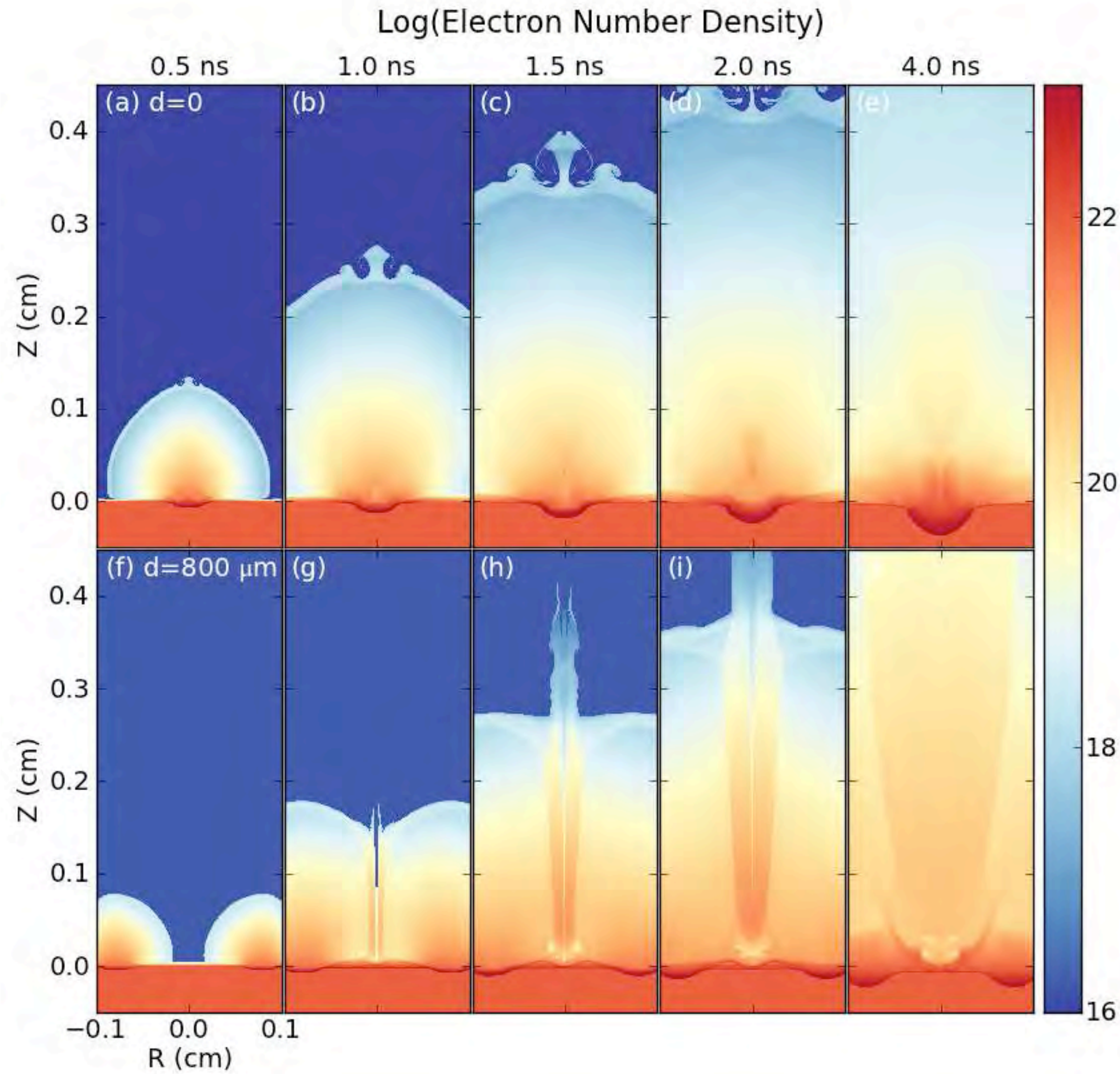


Fig.2 Evolution of the plasma jet electron density produced with the 10 Omega beams hitting the same target spot (top row), compared to a ring pattern of radius d= 800 μm (bottom row) (from Fu et al PRL submitted 2012).

While these results are obtained for Omega laser parameters, it is clear that the ring laser configuration is much more suited for the NIF platform, since NIF has so many more beams to form a more uniform ring of larger radius. Different NIF beams can in principle be also staged in time to form a longer-duration ring laser pulse, which we believe will provide an even stronger collimated outflow. We therefore strongly recommend that future ACSEL collisionless shock experiments at NIF to explore using the ring laser configuration. A subgroup of the ACSEL consortium can be formed to pursue this option, in parallel with the main effort which uses the design of a single target spot for all laser beams. Of course, proof-of-principle experiments of the ring laser configuration should be first demonstrated using the Omega laser before serious experiments at NIF can be pursued.

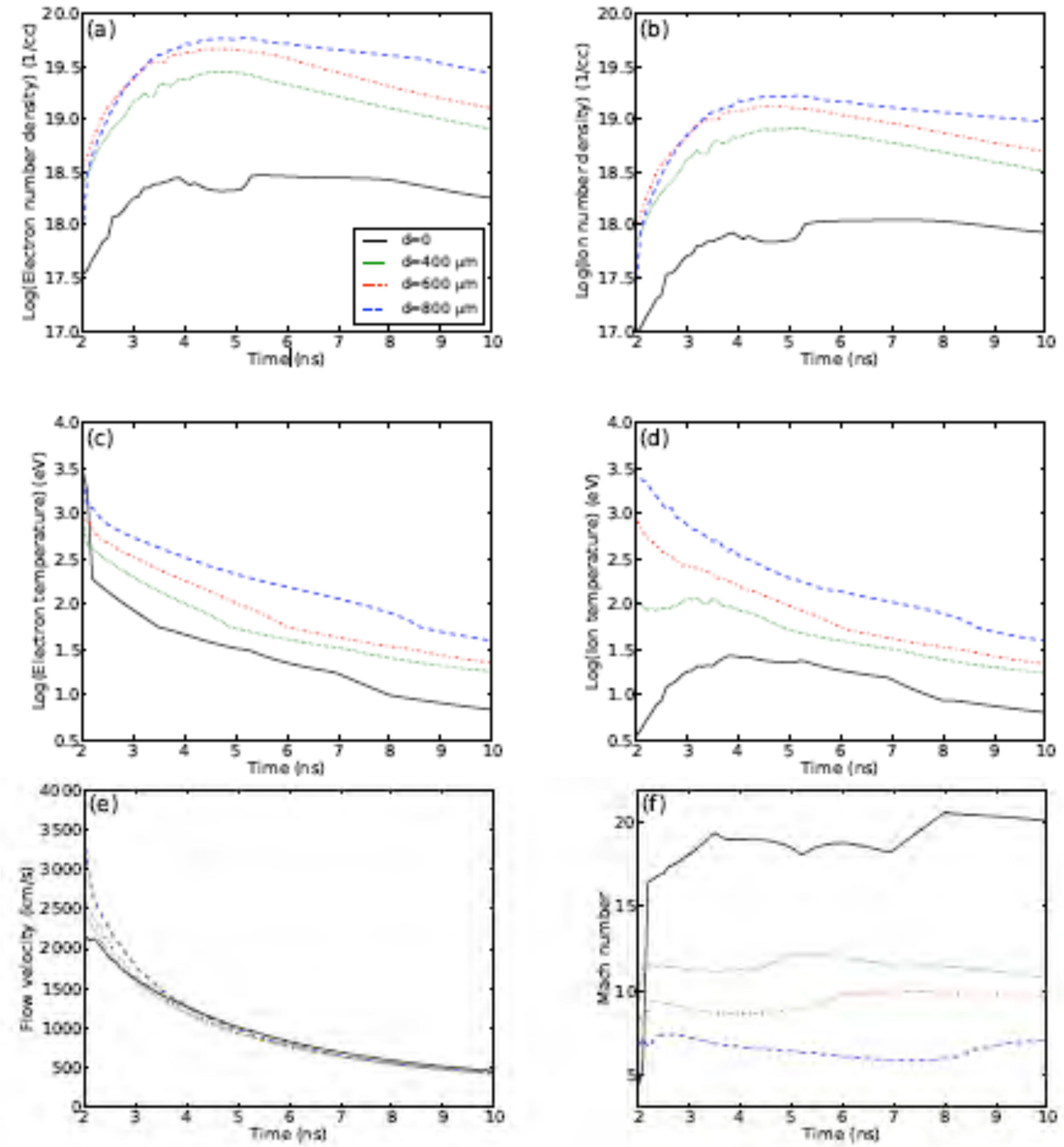
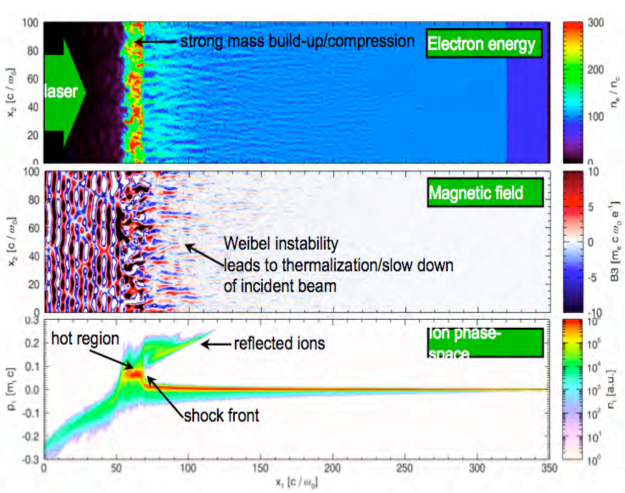


Fig.3 (a) Plot of electron density at 4 mm distance from laser target versus time for different ring laser radii d in microns (inset). This shows that the maximum on-axis electron density is more than twenty times higher for d=800 microns than for d=0. (b) Plot of ion density at 4 mm distance from laser target versus time for different ring laser radii (color codes same as in (a). (c) Plot of electron temperature at 4 mm distance from target versus time for different ring laser radii (color codes same as in (a). (d) Plot of ion temperature at 4 mm distance from target versus time for different ring laser radii (color codes same as in (a)). (e) Plot of flow velocity at 4 mm distance from target versus time for different ring laser radii (color codes same as in (a)). The maximum flow velocity is 60% higher for d=800 microns than for d=0. (f) Plot of Mach number at 4 mm distance from target versus time for different ring laser radii (color codes same as in (a). The laser parameters are equivalent to 10 Omega beams. (from Fu et al PRL submitted 2012).

2. Concept Development for Relativistic Collisionless Shocks

Relativistic collisionless shocks can potentially be created using short pulse high energy lasers with intensity exceeding 10^{19} W.cm^{-2}. For NIF, this will have to wait for the completion of the ARC beams. Two different approaches have been considered. The first is to use the ultraintense laser to irradiate a solid (or at least overdense) low-Z target, directly driving hot electrons into the overdense material using the ponderomotive (**j x B**) force. Provided that the hot electron flux is sufficiently large and the laser pulse sufficiently long, the electrons will strongly couple to the ions and lead to shock-like structures via both electrostatic and electromagnetic instabilities (Fiuza et al 2009, poster presented at ICHED Conf. in Lisbon, unpublished). Even though the laser-driven hot electrons are relativistic, the ions are not. Hence the maximum (ion) shock velocity achievable in this scheme is at most mildly relativistic ($v_{sh} <$ 0.1 c). Nonetheless particle-in-cell (PIC) simulations (Fiuza et al 2009) show that such mildly relativistic shocks exhibit many of the features and properties of relativistic shocks, including magnetic field generation by the Weibel instability and particle energization (Fig.5). The second approach is to use relativistic electron-positron pair jets created by irradiating thick gold targets with petawatt-class lasers. Results from recent experiments suggest that such pair jets can reach bulk flow Lorentz factors of 40 or greater. It has been proposed that a relativistic shock may be achieved by the head-on collision of two such pair jets, if the pair density and column density are sufficiently high (Fig.6). However, such pair jets are likely charge non-neutral (electron density >> positron density). Hence any shock formation and structure will be dominated by electrostatic forces, very different astrophysical shocks. It remains to be convincingly demonstrated using PIC simulations that any "shock" can form in such pair jet collisions. Given the current delays and budget constraints on the ARC beams, it now appears unlikely that two colliding dense e+e- pair jets can be achieved using the NIF-ARC within the next few years. Hence other alternatives for relativistic collisionless shocks must be pursued.



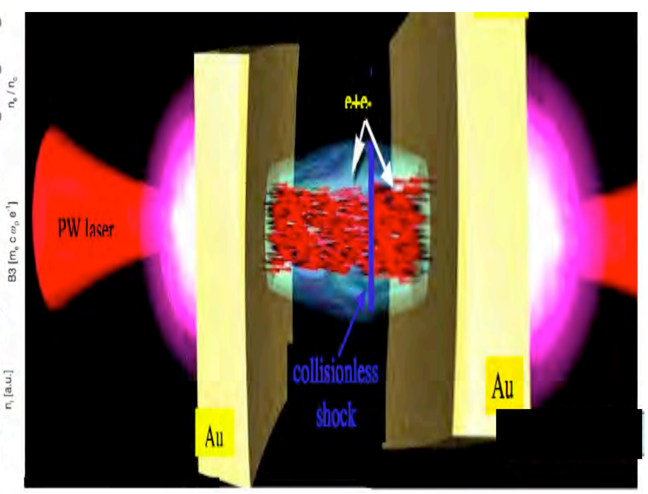


Fig.4 (left) 2D PIC simulation of a 10^{20}W.cm^{-2} laser driving a hot electron shock in a solid target. Relativistic hot electrons filament and generate magnetic turbulence via Weibel, resulting in heating and compression of incident electrons, which in turn leads to heating and compression of ions. (Figure courtesy of Fiuza et al. 2009 unpublished).

Fig.5 (right) Artist conception of relativistic shock launched by head-on collision of two multi-MeV e+e- pair jets created by two high-energy PW-class lasers (similar to ARC) irradiating mm-thick gold targets (Figure adapted from original drawing courtesy of S. Wilks).

One alternative to the scheme of Fig.5 we are currently studying is the interaction of a single relativistic pair jet with a stationary target. If the target is an unmagnetized solid or high-density plasma, it is likely that collisional processes will dominate and the pair jet will be quickly dissipated and thermalized before any shock can form. Any transition structure resulting from such interactions will likely be purely collisional. On the other hand, if the target is *strongly magnetized*, such that the electron gyroradius can be made much shorter than the plasma scale height, it is conceivable that collisionless processes can dominate, much as the solar wind forming a collisionless shock in the earth's magnetosphere. For example, if we want to achieve an electron gyroradius $\leq$ 2 microns, the target magnetic field B needs to be $\geq 10^7$Gauss. Currently, such strong fields can only be created using intense lasers. Hence we propose to pursue the design of an experiment in which one short-pulse high-energy laser is used to create an e+e- pair jet, which then interacts with a superstrong magnetic field with $B \geq 10^7$G created by another short pulse high-energy laser. A proof-of-principle experiment may be first pursued using the two Omega-EP beams, while we wait for the NIF-ARC beams to be constructed.

3. Future Work Plans

A. Computer Simulations

Over the next years, we will first complete the ring laser parameter survey using FLASH simulations, migrating from Omega parameters to NIF parameters, and varying the ring radius and laser duration. The next step is to incorporate magnetic fields, which is missing from the FLASH simulations so far. The third step is to study shock formation using reflective wall boundaries and AMR in the FLASH code. This exercise is urgently needed to support the design work for the ACSEL consortium experiments on Omega and NIF headed by Drs. Park (LLNL) and Spitkovsky (Princeton). The fourth step is to generalize the 2-D simulations to 3-D, taking into account the inhomogeneities created by multiple laser spots and beam patterns. The fifth step is to perform full-fledge 3D simulations of two colliding jets. We are getting the full support of the FLASH team to adapt their code for these simulations, and will continue our close collaboration with them for this project.

The primary deliverable of the ring laser jet simulations is an optimized ring laser platform design for NIF-based laboratory astrophysics experiments. This platform will be fine tuned for the ACSEL consortium experiments being pursued at NIF. A secondary deliverable will be a white paper outlining the various other types of laboratory astrophysics experiments besides collisionless shocks, that will maximally benefit from this new jet platform. Both objectives are critical to the NIF basic science plan.

On relativistic collisionless shocks, our goal is to complete at least one series of Particle-in-Cell (PIC) simulations for each of the two approaches described in Sec.2, in order to judge their feasibility and scientific merits. In particular, we are most interested in studying the interaction of a single relativistic pair jet interacting with a superstrong magnetic field, with $B \geq 10^7$ G to see if a magnetized collisionless shock can be formed in the jet plasma. Our team has access to state-of-the-art tools that allow complete simulation of the shock experiments and enable addressing the lab-to-astrophysics scaling issues. For PIC simulations we will extensively use the code TRISTAN-MP developed at Princeton University (Sironi & Spitkovsky, Astrophys.J. 698, 1523, (2009)), which is a massively parallel 3D and 2D electromagnetic code, as well as the SNL PIC code Quicksilver, plus other 2D PIC codes such as Zohar and XOOPIC. TRISTAN-MP has been successfully used to simulate astrophysical shocks and produced direct evidence of shock acceleration via the Fermi process. We will simulate the expected experimental conditions, incorporating effects of finite beam sizes and finite interaction regions to explore the shock appearance in these conditions. We will then mine the PIC simulation outputs to study the imprints of shock formation on the interaction region diagnostics. In addition to in-house computers at Rice and Princeton, we have full access to the supercomputing resources at NERSC (10^6 hrs/yr), the Tera-Grid, LLNL and LANL open clusters.

B. Diagnostic Development

Ultrafast diagnostic of relativistic plasmas is perhaps the biggest challenge, and it has broad programmatic applications beyond collisonless shocks. In additional to improving conventional diagnostics for plasma density, temperature, flow speed and magnetic fields and extending them to the ultrafast (<ps) regime, we are investigating innovative coherent techniques. Using coherent diagnostics has its distinct advantages: phase information can be utilized for interferometric measurements involving a probe and a reference pulse, such as, for example, frequency-domain holography (Matlis et. al. Nat. Phys. 2, 749, 2006). For many purposes, however, incoherent pulses are sufficient as long as their spectra modified by the scattering from a moving (shock) front can be retrieved. Using multiple probe beams may yield additional information about the evolution of the shock fronts. Our team is developing numerical tools that will model both coherent and incoherent diagnostic beams, as well as various probing geometries. Non-collinear probing geometries present special opportunities for investigating temporal shock evolution. An example of the obliquely incident pulse and the phase/amplitude streak produced using frequency-domain interferometry is shown in Fig.6.

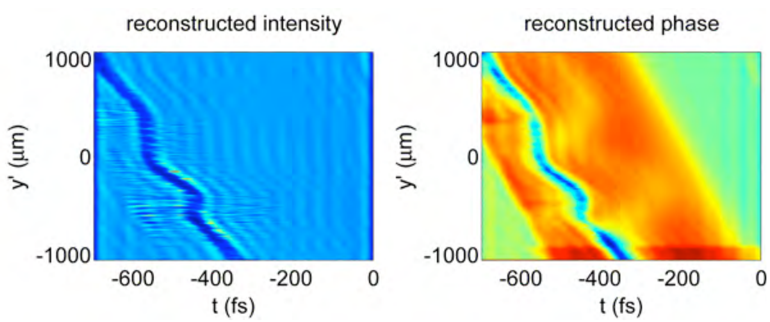


Fig.6: VLPL/photon kinetics simulations of the phase and amplitude streaks produced by the probe pulse crossing the evolving laser bubble at finite angle. Frequency-domain holography is used to extract the phase and amplitude (Shvets, unpublished).

C. Logistics

A critical component of the preparation before the submission of a 5-year NIF experimental proposal will be coordinating and leveraging the team formed for this collisionless shock effort with the existing programmatic work at LLNL and the existing international fast ignition (FI) effort. The existing major programmatic efforts at LLNL and NIF are organized in the form of Integrated Experimental Teams or IETs. An IET exists for each major experimental effort being planned on NIF, such as the national ignition campaign (NIC). Other IETs include the Materials-IET for experiments to probe fundamental material properties at high pressures, the Radiation-IET for experiments to look at complex radiation flow dynamics, and so on. During the coming years, as part of evolving this project into a bona fide NIF experiment proposal, we will form an IET to identify in full detail what would be needed to carry out these experiments successfully. Issues that would be examined are the ARC schedule and parameters, the existing vs. required diagnostics, the DIM configurations, target and diagnostic alignment requirements, unconverted light management issues, target debris and shrapnel considerations, and so on. The detailed results from these assessments would be provided in the 5-year NIF experiment proposal.

D. Resource Requirements

In parallel with the above efforts, our team will carefully assess the personnel and resource requirements before the submission of a 5-year NIF experimental proposal. Ideally we would like to keep the team small and manageable as least in the early phase. We will start with our current team members from Rice, LLNL, Princeton and UT Austin. We will likely bring in additional colleagues from UT, Chicago, LANL and UCSD with the required expertise, who are already collaborating with us on other projects. We are also fully aware that if the early experiments appear promising, the effort may grow rapidly, as in the case of the ACSEL collaboration. The resource required for the NIF 5-year project will scale with both the number and complexity of experiments, and the number of responsible active personnel. This will be formulated based on the experience of and modeled after the ACSEL collaboration.

E. Relativistic Shock Proposal Schedule

At this point, the schedule for NIF-ARC beams is still up in the air. Once that schedule becomes much more well-defined, we plan to work on and submit the relativistic shock experiment proposal at least one year before the ARC beams become operational. Prior to the NIF-ARC experiments, once we have completed the design simulations, we will first propose to the NLUF program for the relativistic shock experiments on Omega-EP. Separately, the ring laser experiments for nonrelativistic shocks will be proposed and pursued as part of the ACSEL collaboration experiments, at both Omega and NIF. That project is independent of the ARC schedule.

4. Personnel and Publications

Two Rice University postdocs, Dr. Xin Wang and Dr. Wen Fu, were partially supported by NIF Concept Development Grant B595752. Dr. Wang worked on PIC simulations of laser-plasma interactions, and Dr. Fu worked on the ring laser jet simulations using the FLASH code.

Publications partially supported by LLNL Grant B595752:

1. “High Energy Astrophysics Experiments using Ultra-intense Lasers”, E. Liang, B. Remington and D. Ryutov, Nature Physics invited review, under revision (2012).
2. “Magnetic Field Generation and Particle Energization at Relativistic Shear Boundaries in Collisionless Electron-Positron Plasmas”, E. Liang et al. Phys. Rev. Lett. submitted (2012).
3. “Monoenergetic Ion Acceleration using Double-Layer Thin Foils”, X. Wang et al. Phys. Of Plasmas in press (2012).
4. “Studying Astrophysical Collisionless Shocks with Counter-streaming Plasmas from High Power Lasers”, H.S. Park et al HEDP 8, 38 (2012).
5. “Characterizing Counter-streaming Interpenetrating Plasmas relevant to Astrophysical Collisionless Shocks”, J.S. Ross et al Phys. Of Plasmas in press (2012).
6.“Hot Electron and Pair Production from the Texas PetaWatt Laser Irradiating Thick Gold Targets**”,** D. Taylor et al. HEDLA2012 Conf. Proceedings, HEDP in press (2012).
7. “Gamma-Ray and Pair Creation using Ultra-intense Lasers and Astrophysical Applications”, E. Liang, HEDP in press (2012).